Fast Correction Coils for Linear Induction Accelerators*

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Abstract

In order to correct transverse beam motion during a 50 ns duration beam pulse, a set of coils has been designed with drive power in the 3 MW range to operate at a bandwidth of 50 MHz. A description of the pulser and a particular application is given along with pertinent test data.

Introduction

The fast correction coil system for the Advanced Test Accelerator (ATA) at Lawrence Livermore National Laboratory (LLNL) is a set of coils, pulsers, and amplifiers that provide wide-bandwidth transverse magnetic fields to correct the position and angle of an electron beam pulse. Beam position monitors or "beam bugs" along the beam line sense the beam position and angle and produce error signals. These signals are applied to function generators which, in turn, drive amplifiers that drive the coils that produce the correcting fields.

The amplifiers are wideband devices based on planar triodes. Each tube can drive up to 12 A at up to 15 kV with bandwidths limited by the circuit application. The tubes can be operated in parallel and provide a source of multimegawatt power.

The ATA output beam is fed into a focusing lens and then into two correction coil stations. The first station corrects beam offset, while the second corrects angle. Each corrects in both the x and y directions. Each station consists of four 60-cm-long rods placed symmetrically about the beam at a radius of about 6 cm. The size and position of the rods is selected to obtain 100 Ω impedance. After the second station the beam passes through another focus coil and into two beam position monitors that measure beam current, position, and angle. These beam bugs are used with an algorithm to generate error signals, which are averaged over several pulses to generate a typical error signal. This signal is digitized and stored in an arbitrary-function generator and subsequently amplified by the planar triode amplifiers to produce pulses of up to 480 A. These pulses, when applied to the four rods, give rise to a 600 G-cm field, which is sufficiently strong to correct anticipated beam errors and to overcome required bias fields.

In the sections below we discuss:

1. The physics objectives.
2. The coil design.
3. The amplifier circuit design.
4. Feed-through and interconnections.
5. The controls and controls algorithm.

In addition, the references list two other papers in this conference that further discuss topics 2 and 3.

Physics Objectives

Because focusing strength of the solenoidal guide field in an accelerator is energy-dependent, an initial offset electron beam will result in a time-dependent transverse displacement of the electron as it traverses the accelerator. This time-dependent displacement, called "corkscrew," is illustrated in Fig. 1. The frequency of the sweep (corkscrew) is roughly given by

$$\omega_s = \frac{1}{\tau_0}\frac{\Delta\gamma}{\gamma_0}\int_0^z k_c \, dz \quad ,$$

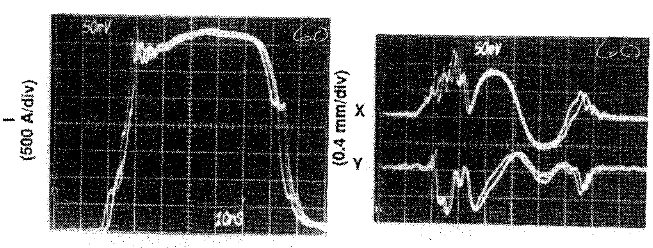
where ω_s is the angular frequency of the sweep, k_c is the cyclotron wave number, γ_0 is the final beam energy, and $\Delta\gamma$ is the energy variation over the pulse length τ_0. For minimum phase advance, a solenoid field tune ending up with 3-kG at 10 MeV and an energy spread $\Delta\gamma/\gamma = 0.03$ over 40 ns, we find $\omega_s\tau_0 \sim 2\pi$ (f_s = 25 MHz). This is the frequency of the sweep between the fiducials shown in Fig. 1. The sweep frequency sets the minimum bandwidth of the correction coil required to correct the offset of a single pulse.

The amount of shot-to-shot jitter of the electron beam determines the frequency level to which a given sweep can be corrected. Error waveforms are accumulated and stored in the function generators. The generator synthesizes the correction waveform by averaging the stored error waveforms. If the correction applied to a given pulse is proper but out of phase with the electron beam, then the resulting phase error, $\omega_s\tau_J = \psi_J$, causes an imperfect correction. To maximize the effectiveness of the correction scheme, we must minimize the shot-to-shot timing jitter. Figure 2 shows the final offset depending on the phase jitter (ψ_j). Note that although the correction coil bandwidth (30 MHz) is higher than the sweep frequency (25 MHz), the correction is imperfect because of timing jitter.

To correct the beam sweep, the fast coils must be able to zero out the transverse angles associated with the sweep:

$$|X'| \simeq K_c|\Delta X|_{max} \quad .$$

Up to twice this capacity is required both to compensate for this angle and to center the beam on the axis. Thus, the coils should be able to change



Beam current at cell 60 (15 MeV) 3-shot overlay

X and Y beam displacements at cell 60 (15 MeV) 2-shot overlay

Fig. 1. ATA beam current and displacement.

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14. ABSTRACT

In order to correct transverse beam motion during a 50 ns duration beam pulse, a set of coils has been designed with drive power in the 3 MH range to operate at a bandwidth of 50 MHz. A description of the pulser and a particular application is given along with pertinent test data.

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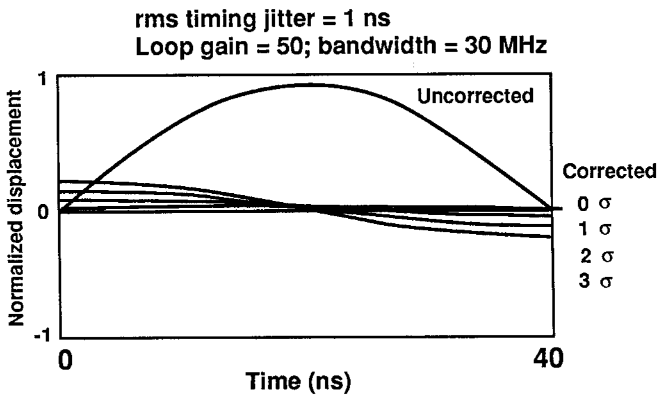

Fig. 2. Dependence of final offset on phase jitter.

the beam angle by ±2 K_c $|\Delta X|_{max}$. For a maximum sweep amplitude of 500 μ in a 3-kG field at 10 MeV, the required correction field is ±300 G-cm. Because the coil power supply is unipolar, we must use an external dc bias field of -300 G-cm so the fast correction coil must supply up to 600 G-cm to overcome the bias and achieve the required ±300 G-cm capability. The basic physics requirements for the fast correction coil are shown in Table 1. The overall specification summary is given in Table 2.

Because the fast correction coils consist of a finite number of rods inside the vacuum system, the transverse correction field will be non uniform over the coil cross section. We used the computer code WIRE to investigate the effect of this non uniformity on the emittance of the electron beam. The beam was assumed to have a 2-cm radius and the correction field to be produced by four wires. There was a small but acceptable degradation of the beam emittance. The transverse field at the edge of the beam was half the value of the field on center. We then use this uniformity as the baseline design point.

Fast Correction Coil Design

The fast correction coil itself consists of an even number of "steering bars" arranged at equal angles within a length of beampipe. A driver circuit feeds one end of each bar through a coaxial transmission line. The opposite end of each steering bar is terminated to the beampipe. Two bars 180° apart form a pair. Pairs are driven with equal but opposite currents.

Table 1. Physics Requirements

Parameter	Minimum required	Design point
Fast correction coil Bandwidth (MHz)	25	40
Fast correction coil strength (G-cm)	± 300 G-cm	± 300 G-cm
Fast correction field uniformity ΔB/B at r=2cm	0.5	0.5
Shot-to-shot jitter (beam) (RMS value)	1 ns	1 ns
Energy variation within e-beam pulse	3%	1.5%
Maximum beam displacement in accelerator (B_Z=3kG)	500 μm	500 μm

Table 2. FCC Summary Chart

Parameter	Design
Coil Bandwidth	40 MHz
Coil Strength	600 G-cm with bias
ΔB/B uniformity at r=2cm	0.5
Shot to shot jitter	1 ns
Energy variation in pulse	1.5%
Max. input beam displacement (Bz-3kG)	500 μm
Required output beam displacement	<100μ
Coil clear space diameter	9.75 cm
Coil length	60 cm
Steering bar diameter	2.07 cm
Number of bars/station	4 at 90 °
Drive current per station unipolar	480 amperes max
Bar impedance	100 Ω
Cable impedance	100 Ω
Beampipe ID	19.51 cm
Circuit risetime	<10 ns
Waveform generators	2 required: Data Precision model2045
Planar triode 32 required per station	Eimac model YU114

In addition to providing sufficient steering field, the coil must be able to deflect the beam in any direction. The steering field must exhibit sufficient uniformity to prevent beam distortion. Also influencing coil design are constraints imposed by other components of the fast corrector system. These constraints include:

- Maintaining 9.75-cm-diam. minimum "clear space" at the center of the beampipe to prevent the beam from striking the steering bars.
- Limiting the maximum coil length to 60 cm. Length is limited by transport considerations and the physical space available.
- Minimizing electromagnetic coupling of the beam with the steering bars to prevent both high induced voltages in the drivers and induced beam instabilities. Coupling is gauged as the per-length mutual inductance, M, between the beam current and each bar.
- Providing a total of 480 A from the driver circuits to excite all four steering bars. Drive signals are unipolar. Driver and cabling considerations limit the impedance of each bar (to beampipe) to 100 Ω or less.

The complexity of the steering system, especially the control subsystem, is reduced by setting the number of steering bars to four. We chose the maximum coil length to minimize the amount of current needed from the driver circuits to achieve a steering field of ±300 G-cm.

The impedance of each 2.07-cm steering bar, referenced to the beampipe wall, is 100 Ω. Lower impedances dramatically increase the required driver current. Each pair of steering bars in the baseline coil design produces the equivalent of a 1-G field per 9.2 A of current. Assuming separate drive circuits are used for each bar, the total current needed is 340 A, well under the 480 A maximum available. The magnitude of the maximum dc bias field is 7.1 G.

Amplifier Circuit Design

The amplifier circuit used to drive the fast correction coils is designed to meet the following requirements:

1. Produce pulses with rise times of less than 10 ns.
2. Supply a maximum of 120 A to opposing sets of steering coils with a positive pulse to one coil and a negative pulse to the other.
3. Drive a total cable impedance of 100 Ω.
4. Attenuate the reflections caused by the termination of the coil ends.
5. Withstand the beam-induced voltages.
6. Successfully operate in an EMI environment
7. Operate in an air-insulated package.

The amplifier employs the circuit designed for the injector energy regulator. This circuit, shown in Fig. 3, uses two parallel Eimac YU114 planar triodes driven in cascode by a power MOSFET. The MOSFET is driven by a buffered, high-speed operational amplifier. An amplifier gain control aids in adjusting system current sharing. The circuit is on a 45-degree pie-shaped printed circuit card that is intended to be mounted in a cylindrical package of eight cards.

Figure 4 is an amplifier system block diagram. Five amplifier modules are packaged in a fourteen inch diameter cylinder. The five amplifier modules are capacitively coupled to a ferrite-isolated splitter/inverter, consisting of two series-driven 50 Ω coaxial cables. The ferrite provides sufficient inductance on the outside of the coaxial shield to isolate the high voltage correction waveform from ground. The 1K resistor to ground is needed to damp out the reflections from the bar termination. Tests indicate that the beam-induced voltage is effectively cancelled. Our circuit has enough voltage margin to accommodate any beam-induced voltage that would arise from an off-center beam. The design of the coil system in the beam pipe should eliminate the possibility of a beam strike on the coils; however, a protective circuit will protect the circuit during tuning, when off center beams are likely.

Feedthroughs and Interconnections

The feedthroughs and interconnecting cable are designed for a 75-kV peak voltage. Voltages in excess of 80 kV will cause a gas breakdown in the feedthrough connector. At the amplifier the voltage induced by the beam will be reduced because of ferrite inversion and bucking of the two pulses, as shown in Fig. 5.

The feed cable has a 50 Ω impedance. One end of each steering bar is shorted. This arrangement minimizes electrostatic steering, doubles current over the 100 Ω case, provides a beam "dump" path, and reduces normal feedthrough stress to 35 kV from 50 kV.

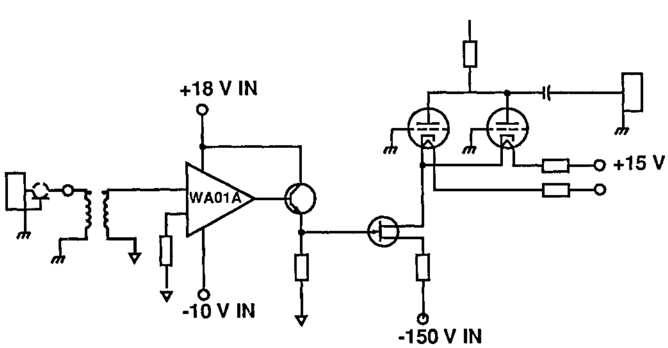

Fig. 3. Fast correction coil amplifier module.

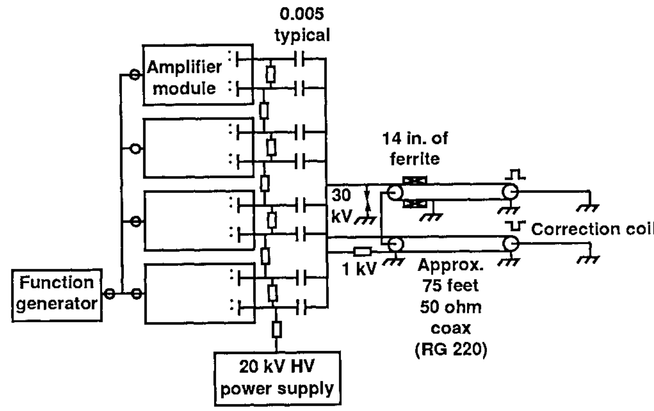

Fig. 4. Fast correction coil amplifier system.

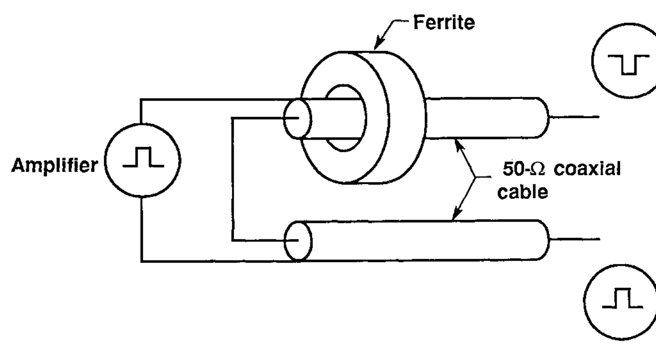

Fig. 5. Ferrite loaded voltage inverting cable transformer.

Controls System and Controls Algorithm

Requirements

Beam trajectory errors in the beam are expected to vary from pulse to pulse within a burst but to be relatively constant from burst to burst for a given pulse. Thus a unique correction waveform is required for each pulse in the burst. This is accomplished by loading all correction waveforms into a computer memory and clocking them out sequentially. The correction waveforms must be clocked out with a 500 MHz clock that is phase synchronous with the accelerator or there will be a 2-ns jitter between the correction waveform and the beam. The best way to do this is to trigger the accelerator from the same 500 MHz clock. The detailed design of the timing system has been completed.

To maximize the useful run time, the control algorithm must generate the proper correction waveforms over a reasonably short period. We will meet this requirement with several techniques. First, the loop gain can be varied to change the acquisition time. When the gain is large, the control system can make large changes to quickly minimize errors. However, the system becomes susceptible to measurement noise. Then, when the error drops, the loop gain is reduced and the system becomes less susceptible to noise, but it also responds more slowly.

Second, an algorithm to identify "bad" shots can be used. Some number of bad shots, or misfires are likely to occur. Data from these shots, if input to the feedback control algorithm, will introduce an undesirable bias that has to be offset by some number of "good" shots. Aternatively, if bad shots are identified, they can be ignored. The algorithm for this purpose has not been developed.

The performance of the FCC control system is limited by two effects: measurement noise and timing jitter. Both can be compensated by reducing the loop gain but only up to a certain limit. Jitter cannot be completely compensated, even under ideal conditions, and is the ultimate limiting factor to overall system performance.

Beamline Configuration

The beamline configuration is shown in Fig. 6. Solenoids 1, 2 and 3 transport a beam whose radius is small enough that nonuniformity of the steering fields will not destroy the beam quality and that the beam will not hit the steering bars or beam pipe. The solenoids are spaced such that beam bugs 1 and 2 must be downstream of solenoid 3. This arrangement complicates the control algorithm because the trajectory through solenoids 2 and 3 must be accounted for. The advantage of placing both beam bugs downstream is that the control system drives both beam bug waveforms toward zero. Their calibrations do not have to be known precisely.

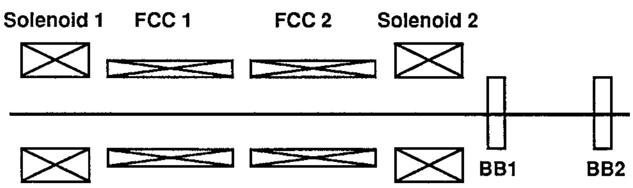

Fig. 6. Fast correction coil beamline layout.

FCC Control System

Figure 7 is a block diagram of the control system. The system will use a dedicated computer and commercial software designed for data acquisition and analysis applications. This approach will significantly reduce the need for custom software. In addition, applications can be easily mdoified to adapt to future changes.

The waveform generators have 512k of memory and can be externally clocked at up to 800 samples/s. The vertical resolution is nominally 8 bits. The transient digitizers have long internal memory and 9 bits of vertical resolution.

The pulser drive circuit is shown in Fig. 8. The diamond-shaped area inside the steering coils

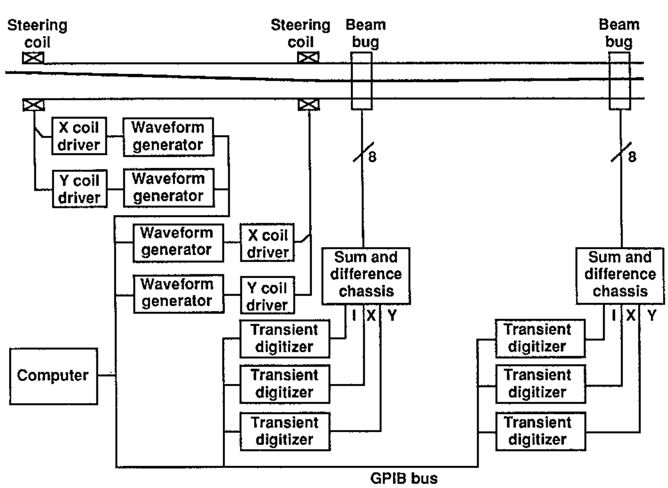

Fig. 7. Fast correction coil controls block diagram.

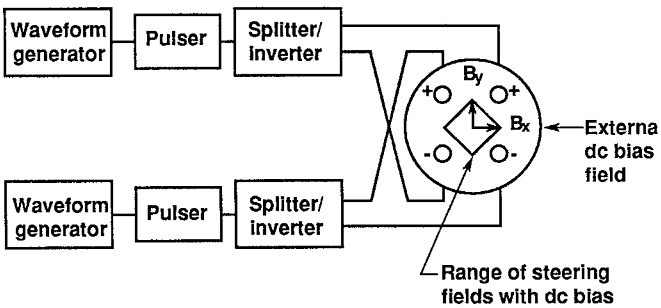

Fig. 8. Block diagram of pulser driver circuit.

represents the possible steering correction range. Since the pulsers are unipolar, an external magnetic field is applied to center the steering range within the pipe. The waveforms driving the two sets of steering bars are functions of both the steering fields. The coupled waveforms are computed as part of the steering algorithm. The splitter/inverters generate positive and negative waveforms of equal amplitude so that midplane symmetry is assured.

Control Algorithm Modeling

We are modeling the control system with the LabView software package, which will also be used for the completed control system. By doing so, we can test the actual control algorithm software off-line.

Waveforms incorporated within the model permit dependent effects within a pulse as well as pulse-to-pulse effects to be analyzed. The model includes beam-bug measurement noise, time shifts between pulser and beam, pulser and FCC impulse response, and feedback loop gain. Results to date indicate that the system is robust in the presence of noise. The standard deviation of the beam position errors is approximately equal to the standard deviation of the additive measurement noise. Reducing the loop gain reduces the beam position errors below the measurement noise, as expected. The pulser impulse response increases the number of iterations for the loop to converge, but using a deconvolution algorithm to predistort the pulser drive signal overcomes this limitation.

Conclusion

One FCC pulser and coil station has been prototyped successfully. Recent preliminary tests on ATA are promising. Beam induced voltage appears to be as calculated and tractable. Other aspects of the test await analysis and will be reported later.

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